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Dielectric spectroscopy of *p-n* junction diodes

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Abstract : The dynamics of the electronic transitions arising from deep levels in the space charge region of a *p-n* junction has been studied by the dielectric spectroscopy of semiconductor (DSS) technique over a frequency range $10^{-2} - 10^{4}$ Hz which is further extended by the variation of temperature in the range 200–300 K A strong non-Debye or non-exponential time dependence of trapping/detrapping processes is found in three *p-n* junctions fabricated on very high resistivity silicon. Dissado-Hill *Spectral-Shape-Function* has been applied to the experimental results which implies that the trapping/detrapping processes follow a fractional power law contrary to the normally believed exponential law A fractional power law behavior is attributed to the correlated electronic transitions according to the Dissado-Hill theory.

Keywords : Dielectric spectroscopy, *p-n* junction, Dissado-Hill theory

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1. Introduction

The electronic transitions occurring between a deep level and one of the free bands in the space charge region of a semiconductor *p-n* junction or Schottky barrier, which is a perfect dielectric to a first approximation, are analogous to sudden dipolar rotations [1]. These electronic transitions give rise to delayed emission of charges when excited by alternating voltage signal [2,3,4]. Thus, a *p-n* junction or Schottky barrier represents a lossy capacitor whose dielectric loss may vary (high or low) depending on the nature and density of deep levels in the space charge region. The frequency response of this lossy capacitor varies to a wide range from the ideal-Debye-like to a frequency-independent or flat loss.

2. Physical model

Consider a *p-n* junction with a shallow donor concentration N_D (not shown) and containing deep levels N_T in the space charge region such that $N_T \ll N_D$ (Figure 1). Charge occupancy of

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only those levels changes which are cut by the Fermi level. Application of a small alternating signal changes the occupancy of the deep levels by alternate emission and capture of charges

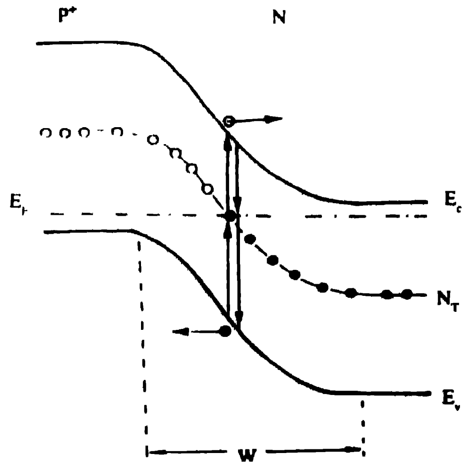

Figure 1. The band diagram of a p-n junction with a donor density N_D (not shown) and a trap density N_T with an activation energy E_T. Capture and release processes are shown by the arrows. A thermally detrapped electron is rapidly transported to the quasi-neutral bulk region by the strong junction field. When these transitions do not follow the applied signal they give a delayed response introducing an out of phase component similar to the dielectric effect

The charges modulated by the signal are the sum of free charges at the edge of the space charge region and charges occupied by the deep levels. The free carriers response falls in the range of dielectric relaxation frequency of the material which is about 10^{12} Hz for device grade silicon. The frequency response of the charges occupied by deep levels depends on the time constant $\tau = 1/\omega_p$ and temperature of the sample. The frequency response is generally between mHz and KHz range. At frequencies much lower than ω_p, the deep levels follow the signal and no dielectric loss occurs. The capacitance is the sum of a low frequency capacitance due to response of the traps and a high frequency capacitance due to free charge modulation at the edge of the space charge region. As the frequency of the signal increases, loss increases and at a frequency equal to the peak frequency the loss is maximum due to delayed response of the traps. On further increase in frequency, deep traps can not follow the signal and loss decreases. At these frequencies the capacitance is only due to the free charge modulation. Thus a finite dispersion ΔC in the capacitance of the p-n junction is due to the change of the occupancy of the deep levels.

There are other processes which also contribute to both real and loss parts. For example, a constant capacitance C_∞, due to processes occurring at the frequencies above the frequencies of interest affects the real part $C'(\omega)$ Similarly, a DC conductance G_0 could affect the loss part due to the process occurring at a faster rate than dielectric loss process. These processes can modify overall shape of the response. A p-n junction may be represented by an equivalent circuit containing a dispersive capacitance in parallel with a conductance. A frequency response of such a circuit is shown in Figure 2. The low frequency part of the peak is affected by the DC contribution such that it can be completely masked by the DC, however the real part may not be influenced.

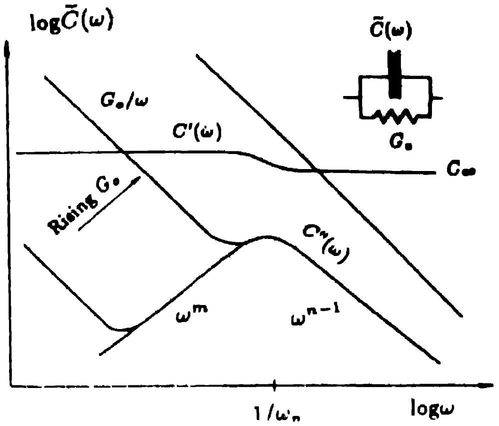

Figure 2. The dielectric response of a dispersive capacitor $C(\omega)$ which includes a high frequency element, C_∞ and a parallel DC conductance G_0, of progressively increasing magnitude whose contribution to the loss, G/ω, gradually swamps the loss peak

The dielectric properties of a *p-n* junction can be expressed in terms of the complex capacitance or its equivalent dielectric susceptibility [5],

$$\tilde{C} = C'(\omega) - iC''(\omega) = \varepsilon_o \frac{A}{d}\left[\varepsilon'(\omega) - i\varepsilon''(\omega)\right] - i\sigma\frac{A}{d\omega} \tag{1}$$

$$= \varepsilon_o \frac{A}{d}\left[\chi'(\omega) + \varepsilon_\infty - i\chi''(\omega)\right] - i\sigma\frac{A}{d\omega},$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the absolute permittivity, A the sample area, d the thickness, ε_∞ the permittivity at high frequencies. $\varepsilon(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega)$ is the frequency dependent permittivity; $\chi(\omega) = \chi'(\omega) - i\chi''(\omega) = \varepsilon(\omega) - \varepsilon_\infty$ the dielectric susceptibility; ω is the circular frequency and σ the conductivity. The loss part is given by :

$$C''(\omega) = \varepsilon_o A/d\left[\varepsilon''(\omega) + G_o/\omega\right], \tag{2}$$

where $G_0 = \sigma A/d$. The loss $C''(\omega)$ is characterized by a peak at frequency ω_p, corresponding to the time constant, τ, of the deep level. In a system where total charges taking part in the dielectric process are limited, such as in a *p-n* junction, the low frequency part is referred to as $C(0)$. The magnitude of the polarization increment $\Delta C = C(0) - C_\infty$ is related to the strength of the loss process and $\tan\delta = C''(\omega)/C'(\omega)$ to magnitude of the loss.

The time dependence of electronic transitions arising from non-interacting deep levels is given by the exponential relation [6] corresponding to the classical Debye relation;

$$P(t) \propto \exp(-t/\tau). \tag{3}$$

Fourier transform of the above equation into frequency-domain is given as [7];

$$\tilde{\chi}(\omega) \propto 1/(1+i\omega\tau),$$

or

$$\tilde{\chi}(\omega) = C'(\omega) - iC''(\omega) - C_\infty = \Delta C/(1 + i\omega\tau). \tag{4}$$

As has been found in the case of dielectrics that the ideal-Debye response is hardly observed in practice [1], a large number of experimental data also point towards the deviation from exponential time-dependence of the trapping/detrapping processes [8-16]. There have been a number of suggestions to explain the non-ideal behavior. For example Queisser [17] has attributed it to the effect of interaction between trapping centers, while Landsberg and Shaban [18] have considered the influence of nonabruptness of the distribution of carrier density at the edge of the depletion region. Jonscher [1] proposed a power law dependence, as found in dielectric materials, to explain spectral shape of the frequency response above and below the loss peak frequency ($\omega_p = 1/\tau$). τ is the characteristic time constant of the deep levels.

Following relations describe the response above ω_p,

$$\tilde{\chi}(\omega) \propto (i\omega)^{n-1} \text{ for } \omega \gg \omega_p,\ 0 < n < 1 \tag{5}$$

and below ω_p,

$$\tilde{\chi}(\omega) \propto (i\omega)^{m} \text{ for } \omega \ll \omega_p\ \ 0 < m < 1 \tag{6}$$

Dissado and Hill [19] presented a cluster model to explain the power law behavior by considering interaction among polarizing species. This *many-body-theory* relates the same power law exponents m and n (eqs. 5 and 6) to the degree of correlation and describes the over all frequency response as well.

The general expression for frequency dependent dielectric susceptibility given by the Dissado-Hill (D-H) theory is

$$\tilde{\chi}(\omega) = \chi(0)F\left(\omega/\omega_p\right), \tag{7}$$

where $\chi(0)$ is the amplitude factor and the entire frequency dependence is represented by the shape function $F = (\omega/\omega_p)$; normalized to the dielectric frequency ω_p which takes the form :

$$F\left(\omega/\omega_p\right) = F_o^{-1}\left(1 + i\omega/\omega_p\right)^{n-1}$$

$${}_2F_1\left[1-n,\ 1-m;\ 2-m;\ 1\Big/\left(1+i\omega/\omega_p\right)\right] \tag{8}$$

F_o is the normalized parameter, given by

$$F_0 = \Gamma(2-n)\Gamma(m)/\Gamma(1+m-n), \tag{9}$$

where Γ ( ) is the gamma function and ${}_2F_1(\cdot\ ;\ ;)$ is the Gaussian hypergeometric function. The asymptotic behavior of eq. (8) at frequencies much below and above the characteristic frequency ω_p describes the fractional power law as given in eqs. (5) and (6).

It has been shown [20] that the generalized dielectric complex capacitance of a sample can be expressed as

$$C(\omega) = S\left[\chi(0)\, F\left(\omega/\omega_p\right) + \varepsilon_\infty\right] - iG_o/\omega, \tag{10}$$

where $S = \varepsilon_0 A/d$ is the geometrical factor.

It will be shown later that in the case of our measurements, the frequency response is strongly non-Debye type and D-H theory is applied which adequately fits the data. The power law exponents m and n are determined by curve fitting.

3. Data analysis

Dielectric data obtained in the raw form might have contribution of other processes such as C_∞ and G_0 as discussed in previous section. It is desirable to eliminate these contributions to obtain a true response. One technique is to perform a Kramers-Kronig transformation which automatically eliminates constants. The other technique is to subtract a constant value manually on point by point basis.

Normalization of the data was carried out using normalization technique given by Hill [21] and Hill and Jonscher [22]. This technique gives a master curve and extends the frequency range. A reliable assessment of the data is then possible and activation energies of the loss processes can be determined from the Arrhenius plots.

Furthermore, if D-H function (eq. 8) is applied to the experimental data, values of the parameters such as m, n, and C_∞ can be determined from the best fit.

4. Samples and experimental procedure

Three diffused p-n junction diodes made on high resistivity silicon (>1000 Ω-cm) obtained from Martin Mariatta Electronics Limited (USA) were studied. The diodes designated M2, M5 and M7 were part of two sets of samples having four diodes in each set. The surface area and thickness of all diodes were 12 mm^2 and 0.5 mm respectively.

Measurements were made with a Solartron Frequency Response Analyzer (FRA) 1250 which is especially adapted for dielectric measurements using Chelsea dielectric interface [23]. The Frequency Response Analyzer performs measurement in the frequency range 10^{-4} – 10^4 Hz in a fully automatic sweep. Diodes were placed in a continuous flow Oxford Instruments CF-104 type cryostat. Oxford Instruments VC-30 flow meter and digital temperature controller DTC-2 having an accuracy of ± 0.1 K were used to vary temperature.

5. Experimental results

The $1/C^2 - V$ plots of the three diodes are shown in Figure 3 which give a diffusion potential of 0.6 volts for all three diodes. The doping density determined for the gradient are given in the table. It is apparent that these diodes have very similar C-V characteristics and are well behaved.

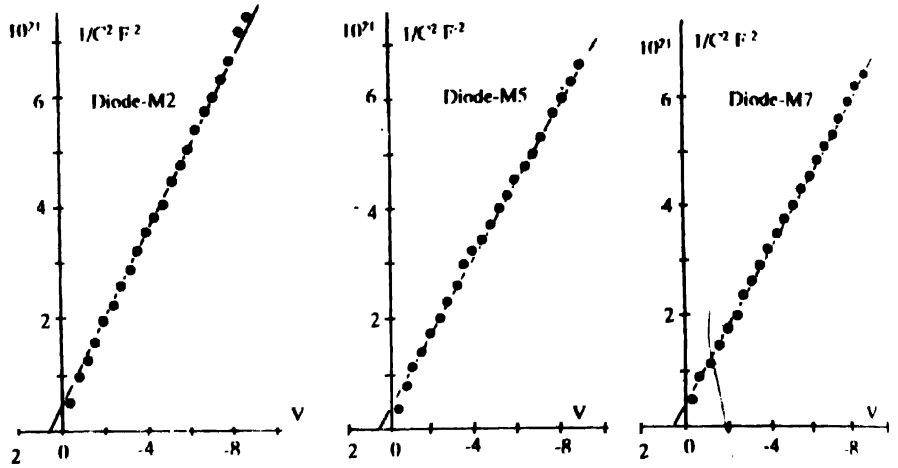

Figure 3. $1/C^2$ *versus* bias plots for diodes M2, M5 and M7 at 300 K. The continuous lines through the experimental points intercept the voltage axes giving the diffusion potential of 0.6 volts for each diode within the experimental error

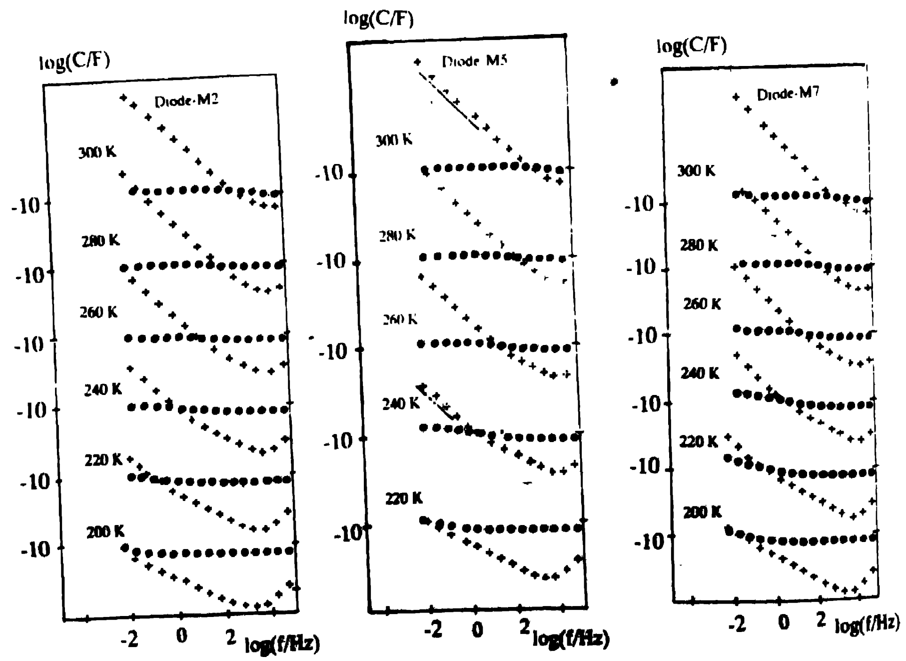

Figure 4. The dielectric response of diodes M2, M5 and M7 at zero bias in the temperature range of 200 K–300 K. Filled circles represent real part $C'(\omega)$ and plus signs loss part $C''(\omega)$. The dominance of DC for the whole temperature range is evident which has masked the loss peaks. The individual data sets are displaced by four decades for clarity.

The dielectric response is shown in Figure 4 for all three diodes in the temperature range of 200 – 300 K. Measurements were performed by applying a 100 mV rms signal and zero bias. The main feature of the data is the domination of DC at frequencies below cross-over frequency of the real and imaginary parts. This is obvious from the fact that the loss is proportional to $1/\omega$, although this trend is not followed at lower temperatures. However, the real part has not been affected by the DC mechanism.

The DC contribution was subtracted from the loss data in order to recover the loss peak for each data set and then normalization was carried out. The DC values subtracted from the original data are plotted against reciprocal of temperature ($1/T$) as shown in Figure 5.

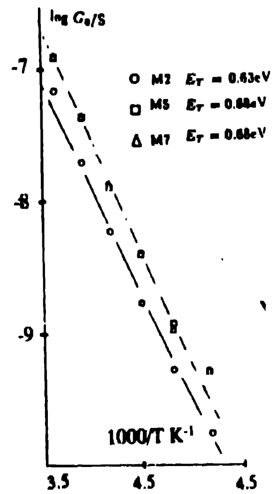

Figure 5. Activation energy plot of diodes M2, M5 and M7 for DC values, G_0, subtracted from the dielectric response (Figure 4)

A reasonably good straight line is obtained for each diode. Diodes M5 and M7 show the same trend Activation energies determined from the plots are given in Table 1. The activation energies correspond to deep levels close to mid-gap energies.

Table 1. Activation energies ΔE determined from the Arrhenius plots

Diode	ΔE eV		m	n	ω_p Hz	Dop.den. $\times 10^{12}$cm^{-3}
	diel.	DC				
M2	0.58	0.63	0.7	0.60	1000	1.0
M5	0.66 / 0.33	0.68	0.7	0.65	20	1.2
M7	0.42	0.68	0.7	0.65	30	1.2

Normalized plots of the dielectric data are shown in Figures 6-8 along with the corresponding Arrhenius plots. A good normalization is obtained in each case and the Arrhenius plots give reasonably good straight lines.

The loss peaks are broader than the ideal-Debye peak for which the power law exponents m and n have values 1 and 0 respectively. Activation energies determined from the

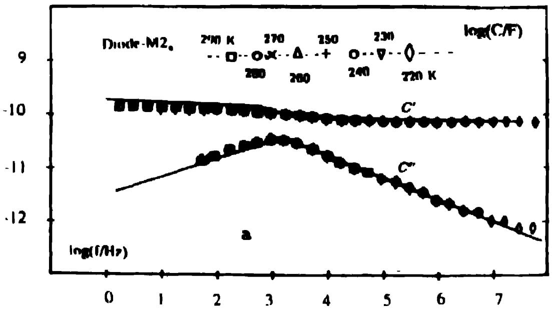

Figure 6. (a) Normalized data of diode M2 after subtracting DC contribution The locus of the temperature points shows almost horizontal displacement.

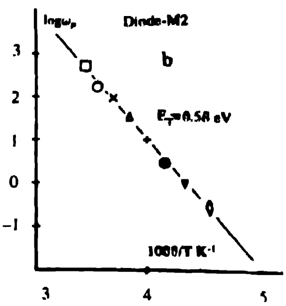

Figure 6. (b) Arrhenius plot gives straight line for the whole temperature range

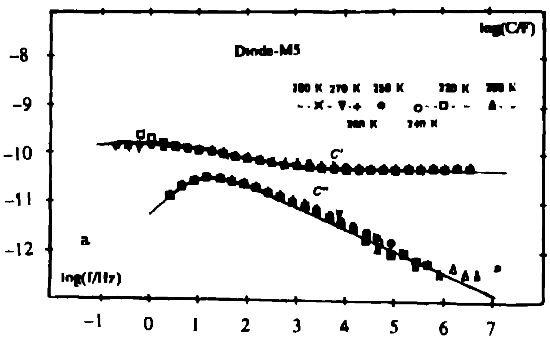

Figure 7. (a) Normalized data of diodes M5 after subtracting DC contribution The locus of the temperature points shows horizontal shift only

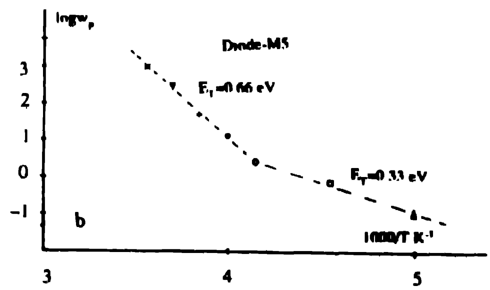

Figure 7. (b) Arrhenius plot of the loss part giving rise to two straight lines corresponding to two different activation energies

Arrhenius plots, correspond to deep levels and are given in the table. The Arrhenius plot of diode M5 gives two activation energies implying two different centers are involved with the same characteristics. It is obvious that deep levels are also involved in dielectric loss mechanism. The values of loss tangent, tan δ, at peak frequencies are in the range of 0.2 to 0.4 while background loss is about 10^{-2}.

Since different deep levels are involved in both DC and dielectric loss processes, this implies that the two processes are independent of each other. A comparison of the DC and dielectric activation energies indicates that the DC activation energies are higher in values as expected [15].

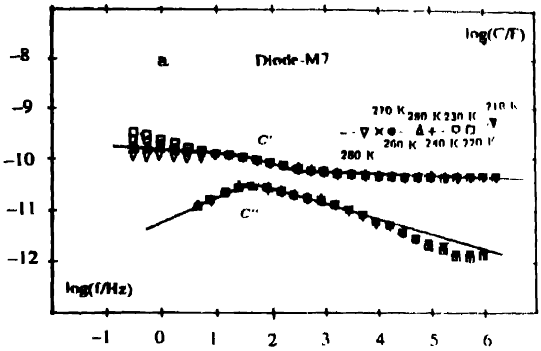

Figure 8. (a) Normalized data of diode M7 at zero bias after subtracting DC contribution. The real part shows a scatter at low frequencies which is also evident from the rise in the locus of the temperature points

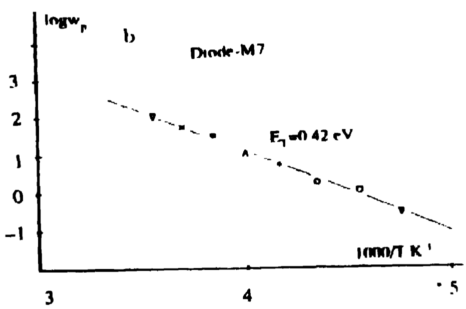

Figure 8. (b) Arrhenius plot of the peak frequency giving rise to a straight line.

The motivation for the present study was to investigate spectral response of deep levels rather than the determination of their parameters such as capture cross section, type of deep level, that is minority or majority carrier trap and charge state *etc*. The Dissado-Hill function is applied to the experimental data for this purpose. Continuous lines in Figures 6-8 show computer fitting of D-H function on the experimental data. A good fit is obtained for the loss peaks extending to a wider frequency range. The real part has a slight misfit at the lower frequency side of the peaks. This may be due to the fact that the data do not normalize completely at that part of the frequency. The parameters determined from the fit are listed in the table for all diodes. The low frequency power law exponent m of the loss peak is 0.7 for the three diodes. Diodes M5 and M7 have same high frequency power law exponent n which is 0.65 while it is 0.6 for diode M2.

6. Conclusions

The dielectric response of the three junction diodes show strong deviation from the ideal-Debye response. The dielectric loss of all diodes seems to be arising from deep levels and is overwhelmingly influenced by the DC which is also found to be activated.

The D-H function is applied to the dielectric response of the *p-n* junctions where the loss processes are entirely different from the usual dielectric processes. The fitting brings out two important features of the experimental data : firstly, the response is strongly of non-Debye type which is obvious from the values of the power law exponents *m* and *n* determined through curve fitting. Secondly, the peaks are asymmetric and peak frequencies of diodes M5 and M7 are quite close as their dc conductance and C-V, I-V [24] characteristics are also very similar. A successful application of D-H theory implies that the non-Debye type response of the detrapping processes may be the result of *Many-body-interaction* of the trapping centers

It has been shown that the D-H theory which was originally developed to explain dipolar response can be applied to trapping/detrapping processes in semiconductors as well However, a theoretical model considering non-exponential time dependence of the trapping/detrapping processes is needed to be developed.

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